PRINCETON, N. J.

Technical Paper 115 Petroleum Technology 26

DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
VAN. H. MANNING, ACTING DIRECTOR

INFLAMMABILITY OF MIXTURES OF GASOLINE VAPOR AND AIR

BY

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WASHINGTON
GOVERNMENT PRINTING OFFICE
1915

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First edition. August, 1915

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INFLAMMABILITY OF MIXTURES OF GASOLINE VAPOR AND AIR.

By G. A. Burrell and H. T. Boyd.

INTRODUCTION.

This paper, which is published by the Bureau of Mines as one of its publications on safety and efficiency in the use of fuels, deals with the inflammable limits of mixtures of gasoline vapor and air and the methods of determining the content of gasoline vapor in such mixtures, matters of importance in ascertaining the risks involved in the storage and use of gasoline.

METHOD OF DETERMINING GASOLINE VAPOR IN MIXTURES.

One of the methods employed in determining the content of gasoline vapor was essentially the same as that used by the bureau to determine the content of benzene in artificial illuminating gas,[a] except that lower temperatures were used. Briefly stated, this method consists in introducing the mixture of gasoline vapor and air into a glass vessel at atmospheric pressure, cooling it by means of liquid air, and then withdrawing the air with a vacuum pump. The stopcock on the liquefaction bulb is closed, and the liquid air removed, thereby allowing the gasoline to vaporize. The pressure of the gasoline vapor is then read by means of a manometer attached to the liquefaction bulb.

G. A. Hulett, consulting chemist of the Bureau of Mines, suggested to the authors this method of analysis for determining water vapor in air, and it was easily applied to benzene vapor, gasoline vapor, or other vapors in air. The chief requirement is that the vapor be cooled to such a temperature that its pressure is practically zero. The investigations showed that the temperature of solid carbon dioxide and acetone (about −78° C.), although low enough to retain benzene (boiling point, 80° C.), was not low enough to retain the gasoline used by the authors, which had a specific gravity at 15° C. of 0.689 (73.2° B.).

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[a] Burrell, G. A., Seibert, F. M., and Robertson, I. W., Analyses of natural gas and illuminating gas by fractional distillation at low temperatures and pressures: Tech. Paper 104, Bureau of Mines, 1915, 41 pp., 7 figs.

GASOLINE FRACTIONS AT DIFFERENT TEMPERATURES.

The following fractionation analysis made by E. W. Dean of the petroleum laboratory of the Bureau of Mines shows the fractions obtained at different temperatures. Two hundred grams of the gasoline was distilled in an unjacketed glass flask at the rate of two to three drops per second.

Results of fractionation analysis of gasoline.

Temperature, °C.:	Percentage by weight.
50	0.9
50–60	9.0
60–70	14.5
70–80	14.4
80–90	13.8
90–100	12.9
100–110	10.9
110–120	7.3
120–130	4.9
130–140	3.2
Residue	2.7
Total	94.5
Loss	5.5

As stated before, experiments by the authors have shown that although benzene (boiling point, 80° C.) can be retained at a temperature of −78° C., the gasoline vapor can not. The above fractionation analysis shows why. A considerable part of the gasoline boils at temperatures lower than 80° C.; hence a temperature that will retain benzene vapor will not necessarily retain the gasoline vapor.

As a temperature lower than that of solid carbon dioxide and acetone had to be used, the authors found it expedient to use the temperature of liquid air, because liquid air has to be used and time consumed in obtaining temperatures between those of solid carbon dioxide and liquid air.

METHOD OF DETERMINING GASOLINE VAPOR IN GASEOUS MIXTURES.

Figure 1 shows the apparatus for the gasoline-vapor determination. The bulb *a* contains phosphorus pentoxide for removing water vapor. If the latter were not removed it would also be retained at low temperatures and would subsequently exert pressure when measurement was being made of the pressure exerted by the gasoline vapor.

To start a determination the apparatus is connected to a vacuum pump and its air exhausted. The mixture of gasoline vapor and air is then introduced at atmospheric pressure, the barometer is read, and the two bulbs are immersed in liquid air contained in a Dewar flask. After about 10 minutes, the air is removed from the apparatus

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with a vacuum pump. The stopcock on the apparatus is then closed, the liquid air removed, the gasoline allowed to vaporize, and its pressure read on the mercury manometer attached to the apparatus. The ratio of this pressure to the pressure of the atmosphere gives the percentage of gasoline vapor originally in the air.

EARLY EXPERIMENTS BY AUTHORS.

The first work of the authors in analyzing mixtures of gasoline vapor and air was performed by burning the gasoline vapor with air or oxygen, measuring the contraction in volume and carbon dioxide produced, and from the data obtained calculating the percentage of gasoline. The results obtained in the combustion analysis by calculating the data as pentane checked very well with the results obtained by separating the gasoline vapor with liquid air. In other words, the pentane was distilled in largest quantity at first when the gasoline was exposed to the air. Pentane reacts with oxygen as follows: $C_5H_{12}+8O_2=5CO_2+6H_2O$. The contraction is 4 volumes and the carbon dioxide 5 volumes. Hence the carbon dioxide produced by burning a sample of a mixture of gasoline vapor and air can be divided by 5 to obtain the gasoline vapor present; or the contraction can be divided by 4. The authors used the first method in obtaining the data presented in this paper.

The table following shows the data obtained by burning the mixtures of gasoline vapor and air in oxygen, and by separating the gasoline vapor with liquid air. It will be observed that the combustion data, that is, the contraction and CO_2 determinations, agree closely with the reaction that occurs when pentane reacts with oxygen. In other words, the constituents that evaporated from the gasoline in

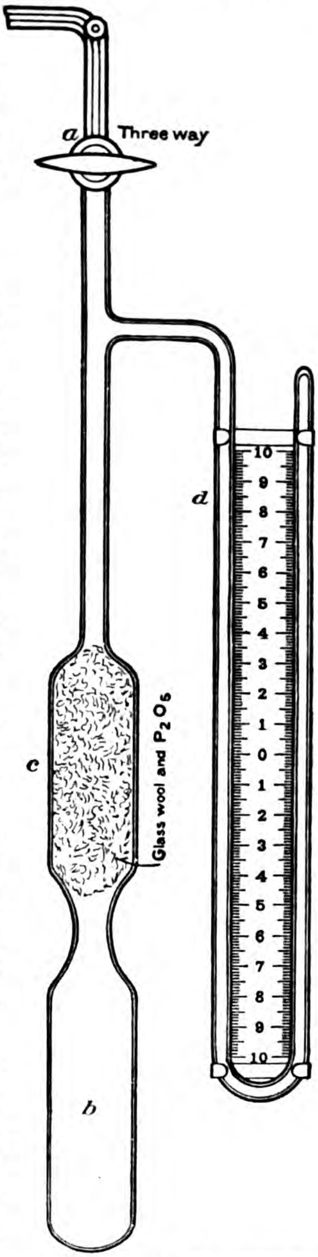

FIGURE 1.—Apparatus for determining gasoline vapor in air. *a*, Three-way cock; *b*, liquifying bulb; *c*, bulb containing phosphorus pentoxide; *d*, pressure gage.

greatest quantity were the pentanes. Heavier hydrocarbons that distil from gasoline can also be calculated from the carbon dioxide and contraction produced.

Results of liquid-air separations and combustion analyses of mixtures of gasoline vapor and air.

LIQUID-AIR SEPARATION.

Item.	Sample No.			
	1	2	3	4
Barometric pressure, mm. Hg	744	748	744	744
Partial pressure of gasoline vapor, mm. Hg	8	19	23	67
Percentage of gasoline vapor	[a] 1.08	[b] 2.40	[c] 3.09	[d] 9.04

COMBUSTION ANALYSIS.

Item.	1	2	3	4
Volume of sample taken, c. c	50.60	46.80	34.58	28.89
Oxygen added, c. c	40.10	46.80	51.16	72.44
Total volume, c. c	90.70	93.60	85.74	101.33
Volume after combustion, c. c	88.55	88.65	81.47	90.75
Contraction, c. c	2.15	4.95	4.27	10.58
Volume after KOH absorption, c. c	85.85	82.46	76.18	77.97
CO_2 produced, c. c	2.70	6.19	5.29	12.78
Percentage of gasoline vapor	[e] 1.07	[f] 2.65	[g] 3.07	[h] 8.86

[a] $\frac{8\times100}{744}$

[b] $\frac{19\times100}{748}$

[c] $\frac{23\times100}{744}$

[d] $\frac{67\times100}{744}$

[e] $\frac{2.70\times100}{5\times50.6}$

[f] $\frac{6.19\times100}{5\times46.80}$

[g] $\frac{5.29\times100}{5\times34.58}$

[h] $\frac{12.78\times100}{5\times28.89}$

In preparing mixtures of gasoline vapor and air for the inflammability experiments, the air was shaken with the gasoline to saturation in a 2,400-c. c. bottle, and then enough of the stock mixture was withdrawn from the bottle and diluted with air to form a desired mixture. The latter was always analyzed prior to exploding it. No precaution was taken to remove water vapor.

TESTS WITH HEMPEL EXPLOSION PIPETTE.

IGNITION AT TOP.

The mixtures were first tested in a Hempel explosion pipette of 100-c. c. capacity, mercury being used as the confining fluid. Near the top of the pipette two platinum wires entered, across which a spark was made to jump by means of an induction coil driven by five dry cells. Inflammation was deemed complete when, upon ignition of the mixture, flame filled the vessel as far as could be judged by the eye. The results follow:

Results of inflammability tests of mixtures of gasoline vapor and air.

Test No.	Percentage of gasoline vapor.	Remarks.	Test No.	Percentage of gasoline vapor.	Remarks.
1	1.8	No visible result.	8	2.0	Complete inflammation.
2	1.9	Do.	9	2.1	Do.
3	1.9	Do.	10	2.1	Do.
4	1.9	Do.	11	2.2	Do.
5	1.9	Do.	12	2.2	Do.
6	2.0	Complete inflammation.	14	3.2	Do.
7	2.0	Do.			Do.

According to the results tabulated above, complete inflammation occurred when the mixtures contained between 1.9 and 2.0 per cent of gasoline vapor. Mixtures containing less gasoline vapor of course underwent some slight burning next the spark, but there was no appreciable propagation of flame in them.

The following results of experiments show the upper limit of complete inflammation of mixtures of gasoline vapor and air as determined by the use of the Hempel pipette, with spark ignition at the top.

Results of experiments to determine upper limit of inflammability of mixtures of gasoline vapor in air, in Hempel pipette; spark ignition at top.

Test No.	Percentage of gasoline vapor.	Remarks.	Test No.	Percentage of gasoline vapor.	Remarks.
1	3.5	Complete inflammation.	6	5.4	Incomplete inflammation.
2	4.8	Do.	7	5.9	Do.
3	5.0	Do.	8	6.0	Do.
4	5.2	Do.	9	6.1	Do.
5	5.3	Incomplete inflammation.	10	6.1	Do.

According to the above tests the upper limit lies between 5.2 and 5.3 per cent of gasoline vapor. With more than 5.3 per cent there was some burning above the spark; for instance, with 5.4 per cent the flame completely filled the small space (about 3 c. c.) above the spark but did not extend below it.

IGNITION AT BOTTOM.

In order to obtain data regarding the influence of the position of the igniting spark on the limits of inflammability, experiments were next conducted under the same conditions as for those just discussed, except that the igniting spark was placed at the bottom of the explosion vessel. The results follow:

Results of experiments to determine the low limit of inflammability of mixtures of gasoline vapor and air; igniting spark at bottom of the pipette.

Test No.	Percentage of gasoline vapor.	Remarks.	Test No.	Percentage of gasoline vapor.	Remarks.
1	2.15	Complete inflammation.	5	1.73	Complete inflammation.
2	2.00	Do.	6	1.62	Do.
3	1.94	Do.	7	1.50	No inflammation.
4	1.78	Do.			

All of these mixtures were analyzed before and after explosion. The gasoline used had a specific gravity of 73° B.

Some flame occurred near the spark in the mixture containing, according to analysis, 1.50 per cent of gasoline, but the combustion was incomplete as only about 0.3 per cent of CO_2 was formed.

The experiments in the Hempel explosion pipette, fired from below, showed a low limit between 1.5 and 1.6 per cent gasoline as against 1.9 to 2 per cent when the mixture was fired from above. They also furnished a good check on the low limit of 1.4 to 1.5 per cent obtained in experiments in a 2,800 c. c. bottle, which are discussed in a subsequent section. There is a difference of only 0.1 per cent. The results tend to show that under the same conditions the greater initial impulse that was obtained by using the large flash had almost no effect upon the low limits of complete propagation of flame, as practically the same results were obtained by a very small spark from an induction coil as by a large flash from drawing apart two heavy copper wires carrying 220 volts and 6 amperes current.

EXPERIMENTS WITH A 2,800 C. C. VESSEL.

Experiments were next tried with a vessel of larger capacity than the 100 c. c. Hempel pipette, the new vessel having a capacity of 2,800 c. c. It was 12 inches (30 cm.) high and 5 inches (12.7 cm.) in diameter. Meeting near the bottom of the jar were two copper wires through which an electric current of 6 amperes at 220-volt pressure could be passed. A flash was produced by drawing these wires apart when current was flowing. The following results show the low limits of complete inflammation as determined in this vessel:

Results of inflammability tests in 2,800-c. c. vessel, showing low limits obtained.

Test No.	Percentage of gasoline vapor.	Remarks.	Test No.	Percentage of gasoline vapor.	Remarks.
1	1.4	Incomplete inflammation.	4	2.3	Complete inflammation.
2	1.5	Complete inflammation.	5	2.5	Do.
3	1.5	Do.	6	2.8	Do.

According to the above results, the low limit of complete inflammation lies between 1.4 and 1.5 per cent of gasoline vapor. With 1.4 per cent of gasoline vapor a tongue of flame about 1 inch at the base, tapering to a cone, extended half through the vessel.

The following data show the high limits determined:

Results of inflammability tests in 2,800-c. c. vessel, showing high limits obtained.

Test No.	Percentage of gasoline vapor.	Remarks.	Test No.	Percentage of gasoline vapor.	Remarks.
1	6.0	Complete inflammation.	3	6.5	Incomplete inflammation.
2	6.4	Incomplete inflammation.	4	6.6	Do.

According to the above results, the high limit of complete inflammation lies between 6.0 and 6.4 per cent of gasoline vapor.

In commenting upon the difference obtained by the two methods of experimentation, it might be added that the investigators of the Bureau of Mines and others have found that lower limits are obtained when ignition is effected from the bottom upward. In the latter case the heated convection currents seemingly rise faster than the flame does, and transmit heat to the unburned gases prior to their ignition by the flame. As a consequence they receive more heat than when ignition is effected from the top, and the mixture inflames with smaller percentages of gas present. Another point brought out by different experimenters is that in small vessels the cooling influence of the walls exerts a marked effect in fixing the limits. For instance, tubes may be of such small bore and hence the cooling influence of the walls so great that flame is not transmitted at all in them. Again, sparks may be so minute as not to ignite the most inflammable mixtures. In such a case the temperature of the spark may be quite above the ignition temperature of the gases, but its duration may be so short that the heat is dissipated before the gases can be raised to their ignition temperature.

INFLAMMABLE LIMITS OF CLEANERS' NAPHTHA.

Further experiments were made to determine whether the inflammable limits of gasoline-air mixtures differed for gasoline of different grades; that is, whether the low limit as determined for gasoline having a specific gravity of 73° B. was different from the low limit of a gasoline having a specific gravity of, say, 59° to 60° B. The gasoline used in the experiments represented in the following tabulation was what is known as cleaners' naphtha, having a specific gravity of 59° to 60° B. The 2,800-c. c. explosion vessel previously described was used.

Results of tests to determine low limit of complete inflammation of mixtures of air and of gasoline vapor from gasoline having a specific gravity of 50° to 60° B.

Test No.	Percentage of gasoline vapor.	Remarks.	Test No.	Percentage of gasoline vapor.	Remarks.
1	2.4	Complete inflammation.	7	1.5	Complete inflammation.
2	2.3	Do.	8	1.5	Do.
3	2.1	Do.	9	1.5	Do.
4	2.0	Do.	10	1.4	Incomplete inflammation.
5	1.8	Do.	11	1.4	Do.
6	1.7	Do.			

According to the results given in the foregoing table complete inflammation, as observed by the eye, took place in a mixture containing 1.5 per cent of gasoline vapor. When a mixture analyzing 1.4

per cent was ignited, inflammation was incomplete, the flame lacking 6 cm. of extending to the top of the explosion vessel.

It was impossible to obtain a mixture containing too much gasoline vapor to explode at the temperature of the laboratory—21° C. The highest mixture obtainable, 4.6 per cent of gasoline vapor, completely inflamed. In other words, the vapor pressure of this particular naphtha at 20° C. is 740 times 0.046, equals 33 mm. of mercury. It would have been possible, of course, by maintaining higher temperatures all through the experiment, to have obtained mixtures of higher gasoline-vapor content.

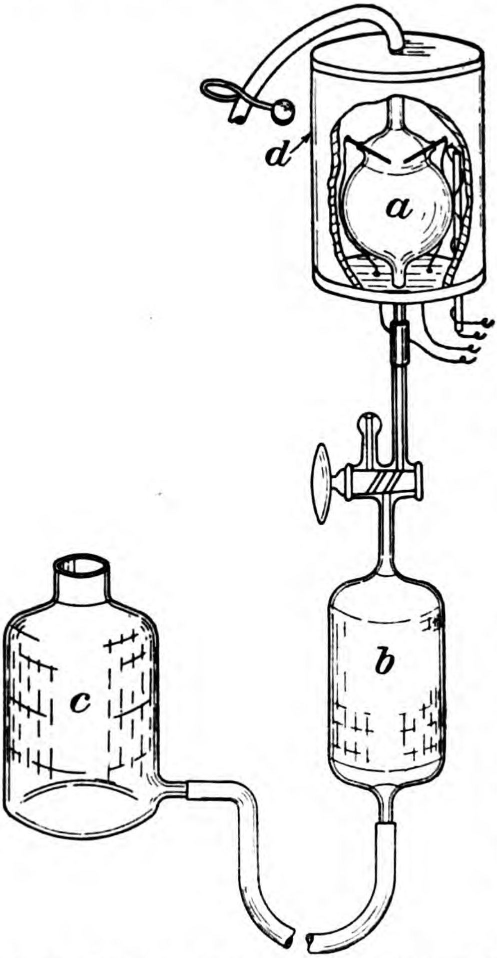

FIGURE 2.—Apparatus for determining effect of increase of initial temperature on low limit of inflammation of mixtures of gasoline vapor and air.

EFFECT OF HIGH INITIAL TEMPERATURES IN SHIFTING LOW LIMIT.

It is interesting to consider the effect of high temperature and pressure to which mixtures of gasoline vapor and air are subjected in the cylinders of internal-combustion engines. A pressure of about 70 pounds per square inch is reached before ignition. The temperature resulting is high because on compression to about 90 pounds per square inch preignition sometimes occurs.

The Bureau of Mines found in experimenting with mixtures of methane and air[a] that when the initial temperature was 500° C., the low limit of complete inflammation was about 3.75 per cent. At ordinary temperature under the particular experimental conditions adopted the low limit was 5.50 per cent. Initial pressures up to 5 atmospheres at ordinary temperatures made no difference in the limits.

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[a] Burrell, G. A., and Oberfell, G. G., The limits of inflammability of mixtures of methane and air: Tech. Paper 119, Bureau of Mines (in press).

In dealing with mixtures of gasoline vapor and air, it was also found that increasing the initial temperature before ignition lowered the low limit appreciably. Experiments were conducted with the apparatus shown in figure 2. In the figure the explosion pipette is shown at *a*. It had a capacity of 100 c. c. Platinum wires were fused in the lower part. A spark from an induction coil, driven by four dry cells, was used to ignite the gas mixtures. An electrically heated oven, *d*, surrounded the explosion pipette *a*. The temperatures were measured by a Pt-PtRh thermocouple.[a] Transparent mica plates were used to close the upper end of the oven in order to observe the effects of sparking the mixtures. At *b* is shown a reserve pipette of 200-c. c. capacity fastened to the explosion pipette by means of pressure tubing.

The apparatus was made ready for use by raising the leveling bottle *c*, thereby completely filling the pipettes *a* and *b* with mercury. The leveling bottle was next lowered until all the mercury had fallen from *a*, leaving a vacuum therein. The stopcock between the two pipettes was then closed. The required gas mixture was then drawn into *b* through the free end of the stopcock, and the oven was heated to the desired temperature, whereupon the gas mixture was introduced into *a* and sparked after two seconds had elapsed. The flame produced, if any, was observed and the products of combustion analyzed.

Preliminary experiments were performed with a thermocouple inserted in the explosion vessel *a* to determine the time required for the gas after it had been introduced into the evacuated bulb to reach the temperature of the oven. It was found that this took place within two seconds after the introduction of the gas.

The table following shows the shifting of the low limit as the initial temperature was increased. The gasoline had a specific gravity of 73° B., the same as that with which the first experiments were made. Ignition was from the bottom upward.

Results of tests to determine effect of increase of initial temperature on low limit of inflammation of mixtures of gasoline vapor and air.

Temperature.	Percentages of gasoline vapor between which low limit lies.	Results of tests according to analyses of mixtures after explosion.
° *C.*		
23	1. 50–1. 62	Complete inflammation with 1.50 per cent.
200	1. 42–1. 50	Complete inflammation with 1.50 per cent.
300	1. 22–1. 28	Complete inflammation with 1.28 per cent.
400	1. 02–1. 22	Complete inflammation at 1.22 per cent.

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[a] This thermocouple was calibrated by J. K. Clement, physicist of the bureau.

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The results presented in the above table show that with increasing temperature the lower limit was shifted until, with an initial temperature of 400° C., the limit was between 1.02 and 1.22 per cent of gasoline vapor. A mixture containing 1.00 per cent of gasoline vapor did not explode when it was heated to 500° C. just prior to ignition, but when it was allowed to stand for one-half hour at this temperature without application of a spark it completely burned. At just what time during the half-hour interval combustion was complete was not determined.

The lowering of the low limit as the initial temperature is increased is owing to the fact that the higher the initial temperature the less heat will be required to raise the temperature of a given mass of the gas to the ignition temperature, and consequently the smaller is the heat of combustion and the percentage of gasoline vapor required to furnish this quantity of heat.

PRODUCTS OF INCOMPLETE COMBUSTION OF MIXTURES OF GASOLINE VAPOR AND AIR.

Of interest in connection with the products of combustion of mixtures of gasoline vapor and air in internal-combustion motors, are experiments the authors performed on these products on a laboratory scale. The mixtures were exploded in a Hempel pipette. After each explosion in the Hempel pipette, the products of combustion were withdrawn and examined.

The table following shows the percentage of gasoline vapor in the mixtures, prior to ignition, and the products of the explosions:

Results of experiments to determine products of combustion of mixtures of gasoline vapor and air.

Number of test.	Percentage of gasoline vapor prior to explosion.	Products of combustion.						
		CO_2	C_nH_{2n}	O_2	CO	H_2	Other combustible gas, chiefly CH_4.	N_2
		Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	5.0	2.8	1.3	9.0	8.4	5.8	....	....
2	4.1	5.2	.0	3.4	14.0	10.3	....	....
3	3.6	7.0	.0	1.7	11.6	6.8	....	....
4	3.0	11.4	.0	1.4	4.1	.5	0.1	82.5
5	2.7	12.1	.0	.6	2.5	.1	.1	84.6
6	2.6	12.9	.0	.5	1.8	.3	.1	84.4
7	2.5	13.8	.0	2.8	.0	.0	.1	83.3
8	2.4	13.0	.0	2.4	.0	.0	.0	84.6
9	2.1	12.0	.0	3.9	.0	.0	.0	84.1

DISCUSSION OF RESULTS.

It will be noticed that, starting with a mixture containing 2.1 per cent of gasoline vapor, the carbon dioxide formed increases to a maximum at 2.5 per cent of gasoline vapor. At this point, as the percentage of gasoline vapor is increased, carbon monoxide begins to form, until at 4.1 per cent there is produced 14.0 per cent of carbon monoxide. In other words, the range of complete combustion for mixtures of gasoline vapor and air is very narrow, between about 1.5 per cent, the low limit, and about 2.5 per cent; therefore it is difficult to run a gasoline engine without producing carbon monoxide at some time. The large amount of oxygen found in the 5 per cent mixture is surprising. This percentage is very close to the upper limit, and during the explosion the flame traveled so slowly it could easily be followed by the eye. There was no lurid flash such as the more active mixtures produced but only a faint blue flame that did not seem to occupy the entire vessel. In other words, the flame apparently did not spread through all of the mixture. Much better combustion is undoubtedly obtained in a gas-engine cylinder with this percentage of gasoline in the mixture admitted. In the engine cylinder the high initial temperature would help furnish the necessary heat to inflame all of the gas mixture. After the determination of CO_2, C_nH_{2n}, O_2, CO and N_2 in the first three samples there remained considerable combustible gas that was chiefly methane, but no attempt was made to determine its composition accurately.

SUMMARY.

Two methods for determining the content of gasoline vapor in air are discussed. One has to do with the introduction of the mixture into an exhausted glass vessel, cooling it at the temperature of liquid air, removal of the air, and finally the measurement of the partial pressure of the gasoline vapor by means of a manometer attached to the liquefaction bulb.

Another method consists in burning the gasoline vapor in oxygen and, from the contraction and carbon dioxide produced, calculating the percentage of gasoline vapor.

When a 100-c. c. Hempel explosion pipette was used and the mixtures were ignited from the top, there was obtained as the lower limit of complete inflammation a value lying between 1.9 and 2.0 per cent of gasoline vapor. The upper limit under these conditions was found to be between 5.2 and 5.3 per cent of gasoline vapor. The gasoline used had a specific gravity of 73° B. Under the same conditions, except that the mixtures were ignited from the bottom, there was obtained a value lying between 1.5 and 1.6 per cent of gasoline vapor as the low limit. With the same grade of gasoline, with a 2,800-c. c. vessel, and with ignition from the bottom by means of an electric flash produced by pulling apart two wires through which a current of 7 amperes at 220 volts was flowing, there was obtained a value lying between 1.4 and 1.5 per cent of gasoline vapor. The high limit under these conditions lay between 6.0 and 6.4 per cent of gasoline vapor.

When the initial temperature is increased before ignition of the mixtures the low limit is gradually decreased until with an initial temperature of 400° C. the low limit lies between 1.02 and 1.22 per cent of gasoline vapor.

The range of complete combustion for mixtures of gasoline vapor and air is very narrow, and is between about 1.5 and 2.5 per cent. The amount of carbon dioxide produced reaches a maximum at 2.5 per cent of gasoline vapor. At this point, as the percentage of gasoline vapor increases, carbon monoxide begins to form. At 4.1 per cent of gasoline vapor there is produced 14.0 per cent of carbon monoxide.

PUBLICATIONS ON PETROLEUM TECHNOLOGY.

A limited supply of the following publications of the Bureau of Mines is temporarily available for free distribution. Requests for all publications can not be granted, and to insure equitable distribution applicants are requested to limit their selection to publications that may be of especial interest to them. Requests for publications should be addressed to the Director, Bureau of Mines.

BULLETIN 19. Physical and chemical properties of the petroleums of the San Joaquin Valley, Cal., by I. C. Allen and W. A. Jacobs, with a chapter on analyses of natural gas from the southern California oil fields, by G. A. Burrell. 1911. 60 pp., 2 pls., 10 figs.

BULLETIN 88. The condensation of gasoline from natural gas, by G. A. Burrell, F. M. Seibert, and G. G. Oberfell. 1915. 106 pp., 6 pls., 18 figs.

TECHNICAL PAPER 3. Specifications for the purchase of fuel oil for the Government, with directions for sampling oil and natural gas, by I. C. Allen. 1911. 13 pp.

TECHNICAL PAPER 10. Liquefied products from natural gas, their properties and uses, by I. C. Allen and G. A. Burrell. 1912. 23 pp.

TECHNICAL PAPER 25. Methods for the determination of water in petroleum and its products, by I. C. Allen and W. A. Jacobs. 1912. 13 pp., 2 figs.

TECHNICAL PAPER 32. The cementing process of excluding water from oil wells as practiced in California, by Ralph Arnold and V. R. Garfias. 1913. 12 pp., 1 fig.

TECHNICAL PAPER 37. Heavy oil as fuel for internal-combustion engines, by I. C. Allen. 1913. 36 pp.

TECHNICAL PAPER 38. Wastes in the production and utilization of natural gas and means for their prevention, by Ralph Arnold and F. G. Clapp. 1913. 29 pp.

TECHNICAL PAPER 42. The prevention of waste of oil and gas from flowing wells in California, with a discussion of special methods used by J. A. Pollard, by Ralph Arnold and V. R. Garfias. 1913. 15 pp., 2 pls., 4 figs.

TECHNICAL PAPER 45. Waste of oil and gas in the Mid-Continent fields, by R. S. Blatchley. 1914. 54 pp., 2 pls., 15 figs.

TECHNICAL PAPER 49. The flash point of oils; methods and apparatus for its determination, by I. C. Allen and A. S. Crossfield. 1913. 31 pp., 2 figs.

TECHNICAL PAPER 51. Possible causes of the decline of oil wells and suggested methods of prolonging yields, by L. G. Huntley. 1913. 32 pp., 9 figs.

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